Liu, Y., Zuo, S., Liang, X., Heidari, H., Khanbareh, H. and Ghannam, R. (2020) Gesture Recognition Wristband Device with Optimised Piezoelectric Energy Harvesters. In: 2020 27th IEEE International Conference on Electronics, Circuits and Systems (ICECS), Glasgow, Scotland, 23-25 Nov 2020, ISBN 9781728160450 (doi:10.1109/ICECS49266.2020.9294809).

Gesture Recognition Wristband Device with Optimised Piezoelectric Energy Harvesters

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***Abstract*—Wearable devices can be used for monitoring vital human physiological signs and for interacting with computers. Due to the limited lifetime of batteries, these devices require novel energy harvesting solutions to ensure uninterrupted and autonomous operation. We therefore developed a wearable wristband device with piezoelectric transducers, which were used for hybrid functionality. These transducers were used for both energy harvesting and sensing applications. In fact, we also demonstrate that gestures can be classified using electricity generated from these piezoelectric transducers as a result of tendon movements around the wrist. In this paper, we demonstrate how a multi-physics simulation model was used to maximize the amount of harvestable energy from these piezoelectric transducers.**

Keywords—piezoelectric sensor, energy harvester, wearable electronics

I. Introduction

People are increasingly spending more time interacting with computers. The capability to estimate intentions from hand gestures has applications across a wide range of fields, including telerobotic surgery, virtual reality, health rehabilitation and mobile computer input, human-robot collaboration [1-4]. Many techniques have been developed to detect hand gestures. There are four main technologies for hand gesture recognition, which are based on cameras, accelerometers (ACC), electromyography (EMG) and pressure sensors.

Camera-based technologies directly capture the gesture video or picture information, followed by processing the depth images of the pixel point to the lens distance [5]. High accuracy, efficiency and robustness make it become a commonly used method in human-computer interaction applications. However, limitations related to viewing angle, sensitivity to lighting conditions and noisy background restrict application scenarios in which cameras can be used [6].

As for ACC-based technology, it is comfortable to wear without disturbing natural hand gestures, and it could provide rich information about hand movements. However, the drawback of the accelerometer-based method is that the detected signal is mixed, and it is always challenging to identify the performance of individual sensor setups. Thus, they cannot receive a separate signal from the palm and finger movements simultaneously [7].

In contrast to other solutions for hand gesture recognition, EMG-based technology provides an important opportunity to achieve natural human-computer interaction by directly sensing and decoding subtle muscle activities [8]. Because of the small electrodes attached on the arm, any subtle wearing position change will strongly influence the accuracy [9]. Meantime, signal and noise will be synchronously collected so that it will increase the complexity of signal processing and analysis.

Pressure-based hand gesture recognition has recently attracted increased attention. Gloves, armband, and wristband become the main applications for collecting the pressure signal for hand gestures. Among these, the wristband is attractive due to its low cost, small size, excellent flexibility and comfort. Our previous work has achieved promising results using capacitive pressure sensors and force sensitive resistor sensors attached to the flexible wristband to capture tendon movements around the wrist [10, 11]. In previous experiments, the wristband was powered via a long USB cable, which was inconvenient as a wearable device. In this case, we aim to achieve a self-powered wristband using novel piezoelectric sensors, which were chosen to act as both the power source and pressure sensors.

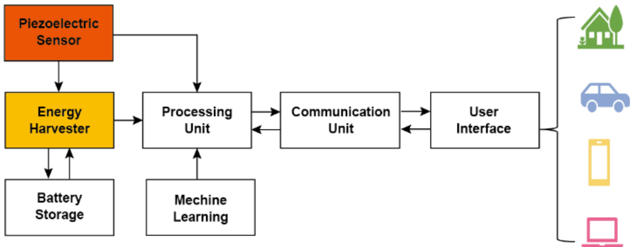

Fig. 1. The block diagram of the smart bracelet.

Fig. 1 shows the basic functions of the wristband system. The bracelet device is designed as an autonomous system to recognize hand gestures. Piezoelectric sensors convert mechanical energy from daily motions to electrical energy that provide the necessary power to the whole system. Meanwhile, these transducers sense tendon movements around the wrist. The active signals are processed through the signal processing unit. Then the useful information is transmitted to terminals such as the computer and the mobile phone with the help of signal communication units.

In this paper, we focus on optimising the dimensions of the piezoelectric sensor to find the best energy harvesting result. A flexible wristband with embedded piezoelectric sensors was simulated by COMSOL Multiphysics. Finite Element Method (FEM) is used to find the optimal dimensions of the sensor in order to generate maximum energy.

This article is organised as follow: the background of the piezoelectric principle and the wristband design are explained in Section II. Section III shows the simulation results and discussion. Conclusion and future work are provided in Section IV.

II. Methodology

A. Background

Mechanical energy is one of the most omnipresent energy sources from the ambient and the human body. It is available in the form of the human body, vehicles, industrial machinery and large-scale buildings [12]. Piezoelectric power harvesting is a popular strategy that converts mechanical energy to electrical energy. The direct piezoelectric effect is the ability of certain crystalline materials to develop an electric charge proportional to the mechanical stress, which was first discovered in quartz by Pierre and Jacques Curie in 1880 [13]. Equation (1) shows the basic principle of the direct piezoelectric effect that is suitable for power harvesting:

$$D = d \cdot T + \varepsilon T \cdot E \qquad (1)$$

where D is the electric displacement, T and E are the stress tensor electric field respectively, εT represents the dielectric permittivity under zero or constant stress, d denotes the direct piezoelectric coefficient [14].

B. Wristband Design

The wristband model was built by Piezoelectricity Multiphysics coupled with Electrical Circuit physics. The wristband was designed according to the realistic human wrist shape and size (see Fig. 2). The 3D hand model was imported from the Solidworks. The structure of the wristband substrate was designed in 2D axial symmetry and then extruded into a 3D model. Then a 3D cylinder was embedded into the substrate, and it worked as the piezoelectric sensor.

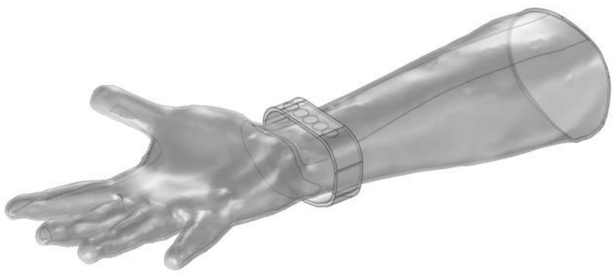

Fig. 3. The concept of the wristband design.

The substate of wristband could affect the performance of the piezoelectric sensors. Choosing a suitable substrate will reduce the interference from the environment and optimise contact with users. Furthermore, a suitable substrate could offer appropriate mechanical support to sensors and ensure they are attached to the wrist tightly to detect most of the subtle movements. In this case, Polydimethylsiloxane (PDMS) material was chosen as the main body of the wristband since it is a flexible, transparent and inert material that is comfortable for hand movements.

The sensor was embedded into the substrate and made sure it is in the middle of the PDMS material. In this paper, we chose the cylindrical PZT-5H sensor to harvest energy from hand movements. Ceramic materials are widely used in piezoelectric applications due to their competitive prices and excellent material properties. The lead zirconate titanate (PZT) based on the solid solutions of $PbZrO_3$ (PZ) and $PbTiO_3$(PT) is the most well-known piezoceramic [8]. The superior piezoelectric properties and commercial availability make PZT ceramics the main choice in the wearable system to harvest energy from the human body. The material properties of both PDMS and PZT-5H are selected from the COMSOL library.

Then the solid mechanics model was used to establish boundary conditions. For the single piezoelectric sensor, the bottom surface was fixed and the top surface was free to vibrate. Whereas, when the sensor was embedded into the flexible substrate, the bottom of the wristband was free and other parts of the substrate were fixed. The force of the wristband varies from the tightness of the substrate. In this paper, a constant 2N force was assumed to apply on the top surface of the piezoelectric transducer or on the inner surface of the wristband.

To calculate the output power and voltage, a 100MΩ resistor was connected between the two surfaces of the piezoelectric sensor. After that, physics-controlled mesh with fine element size was performed on the wristband. In addition, human movements are always within low and random frequencies, which usually occurs around 1Hz [15]. Hence, the performance of the sensor was analysing at 1Hz at frequency-domain study in COMSOL. The detailed information is shown in Fig. 3.

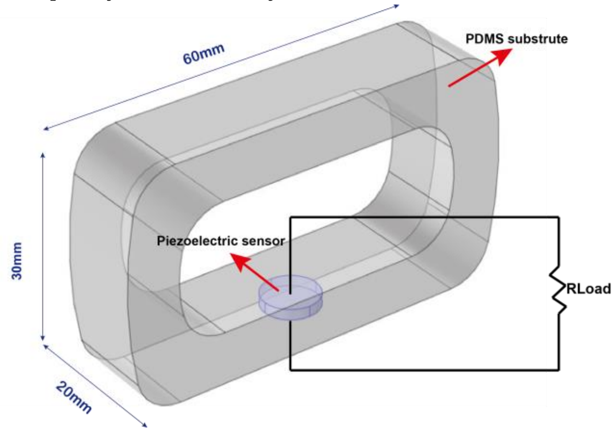

Fig. 2. The basic parameters of the wristband

III. Simulation result and Discussion

The harvested energy of a piezoelectric transducer depends on its geometry, material properties, resonance frequency and the output load [16]. Here, the main focus is what are the optimum dimensions of the piezoelectric sensor to achieve the highest power density. The two main parameters considered are the thickness and the radius of the cylindrical sensor. In this paper, the power density and the output voltage over different radii and thickness are first and then followed by the sensor embedded into a flexible substrate.

A. Piezoelectric sensor alone

Fig. 4(a) shows the output voltage and power density various from the different thicknesses of the sensor when applying force on the top surface of the sensor. Most of the piezoelectric sensors are not too thick in practice in order to avoid discomfort in wearable devices. Here, we aim to investigate the variation in power density, so the thickness of the piezoelectric sensor various from 0.5mm to 10mm was discussed. The radius of the sensor was fixed to 5mm. From the figure, the output voltage increases sharply at first, then reaches a plateau, and the maximum voltage was 0.67V. For the power density, when the sensor was 2.5mm thick, power density had reached the maximum 5.8nW/cm3. This result is similar to the previously published work [17].

Fig. 4(b) illustrates the sensor output performance for different sensor radii. This time we chose the optimise thickness of 2.5mm and swept the radius from 0.5mm to 10mm to find the maximum power density. It is clear that both the output voltage and power density decrease when the radius of the sensor increases.

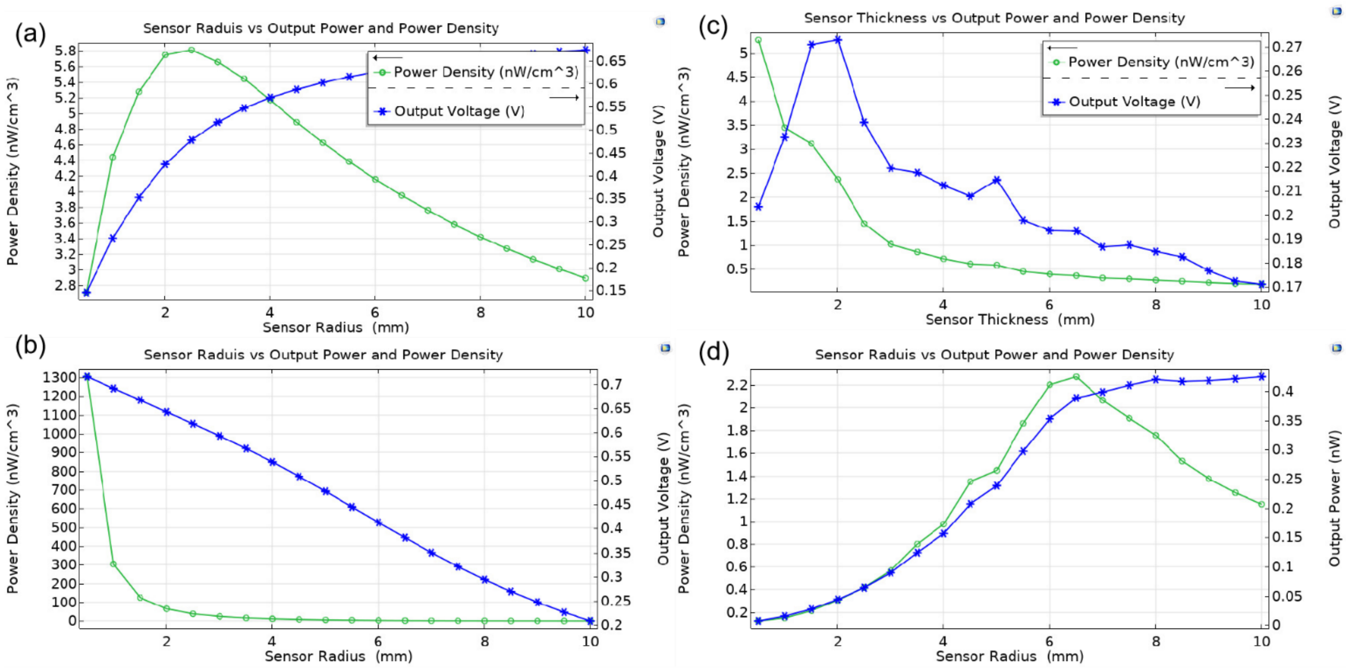

Fig. 4. The simulated output voltage and power density various by piezoelectric sensor dimensions. (a) Change the thickness of the sensor.(b) Change the radius of the sensor. (c) Change the thickness of the sensor when inserting into the PDMS substrate. (d) Change the radius of the sensor when inserting into the PDMS substrate.

B. *Piezoelectric sensor embedded into the wristband*

In our previous experiment [10], PDMS material was used as a flexible substrate to fix the sensors on the wristband. In this case, we embedded the sensor into the PDMS material to investigate how the substrate affects the output performance. As mentioned above, PDMS is a flexible material so that the wristband will be deformed under pressure. The constant force now was applied on the inner surface of the wristband substrate.

From Fig. 4(c), we observe that power density continuously decreases when increasing the sensor thickness. The output voltage has a peak at 0.27 V when the sensor is 2 mm thick. This takes place since increasing the thickness of the sensor decreases the pressure applied to the sensor, as shown in Fig. 5.

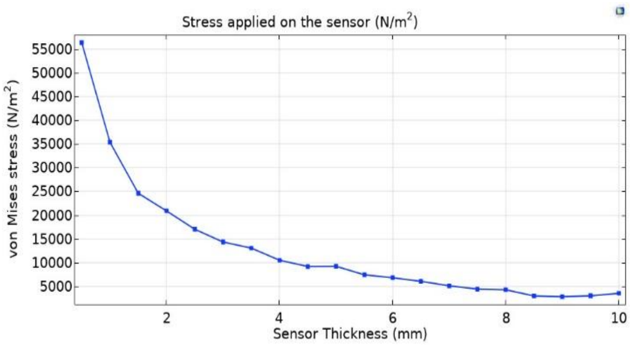

Fig. 5. Stress applied to the sensor decreased while increasing the thickness of the sensor.

Fig. 4(d) shows the output voltage and power density of the piezoelectric sensor when changing the radius. When the thickness is still fixed at 2.5 mm, it can be observed that the power density reaches a peak at 2.3 nW/cm^3 when the radius is 6.5 mm. The maximum output voltage reaches 0.43 V when the radius is 8 mm. The applied pressure on the inner surface of the PDMS substrate is constant since the area of the inner substrate is constant. As the radius of the sensor increased, the stress on the sensor also increased (Fig. 6). Thus, it has an increasing trend of the output voltage when increasing the radius.

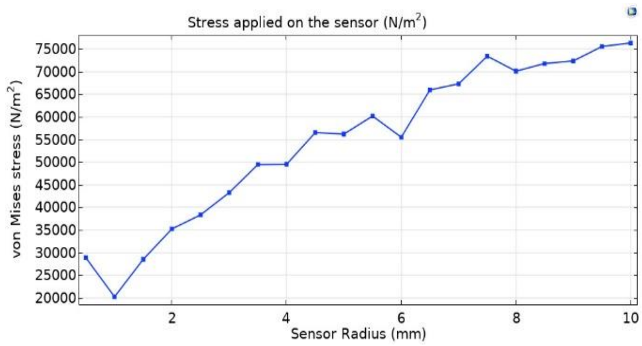

Fig. 6. Stress applied to the sensor increased while increasing the radius of the sensor.

There is a large difference between the performance of piezoelectric sensor alone and embedded into the flexible wristband substrate. When fixing the bottom surface of the piezoelectric sensor and applying force on the top surface, the sensor carried all force. However, in addition to the sensor's deformation, the substrate deformation should also be considered when the sensor is inserted into the flexible substrate. Since the substrate deformation will disperse pressure from the sensor, the applied pressure on the embedded sensor decreases and the maximum power density also decreases.

IV. Conclusion and Future Work

In this paper, we aimed to optimise the dimensions of the cylindrical piezoelectric sensor to find the best performance of energy harvesting based on FEM simulations. The power density is influenced by both thickness and radius of the piezoelectric transducer. The results demonstrate that a cylindrical piezoelectric energy harvester with a thickness of 2.5mm and a smaller radius can obtain the maximum power density. When the sensor embedded into the flexible substrate, the maximum power density can be obtained by decreasing the thickness of the sensor with a fixed radius at 6mm.

The future work will explore the different shapes of the piezoelectric sensor as well as their optimised dimensions for self-power wearable devices. The model of the wristband will be perfected to make it closer to the actual bracelet. Afterwards, the fabricated piezoelectric sensors will compare with the simulation results to examine the performance of the proposed energy harvester.

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